Fatigue Prediction Verification of Fiberglass Hulls

Paul H. Miller

Department of Naval Architecture and Ocean Engineering

U. S. Naval Academy

Why Study Fiberglass Fatigue?

- Approximately 30% of structural materials now used in the marine environment are fiberglass.
- Little long-term fatigue data exists.
- 1998 Coast Guard data shows 118 fiberglass failures resulting in 6 fatalities

This Project's Goals

- **Extend the standard fatigue methods used for metal vessels to composite vessels**
- **Verify the new method by testing coupons, panels and full-size vessels.**

Background-Current ABS <u>Composite</u> Design Methods

- **Semi-empirical, theory and previous vessels**
- **Quasi-static "head"**
- **Beam and <u>isotropic</u> plate equations**
- **Conservative**

<u>Factors of Safety</u>

(Working Stress Design)

- **<u>2.33</u> for bulkheads**
- **<u>3</u> for interior decks**
- **<u>4</u> for hull and exterior decks**

Includes fatigue and uncertainties in loads

Simplified Metal Ship Fatigue Design

1. **Predict wave encounter ship "history"**
2. **Find hull pressures and accelerations using CFD for each condition**
3. **Find hull stresses using FEA**
   - **Wave pressure and surface elevation**
   - **Accelerations**
4. **Use Miner's Rule and S/N data to get fatigue life**

Project Overview

- Material and Application Selection
- Testing (Dry, Wet/Dry, Wet)
  - ASTM Coupons, Panels, Full Size
  - Static and Fatigue
- Analysis
  - Local/Global FEA
  - Statistical and Probabilistic

Material & Application Selection

Ideally they should represent a large fraction of current applications!

- **Polyester Resin (65%)**
- **E-glass (73%)**
- **Balsa Core (30%)**
- **J/24 Class Sailboat**
  - **5000+ built**
  - **Many available locally**
  - **Builder support**
  - **Small crews**

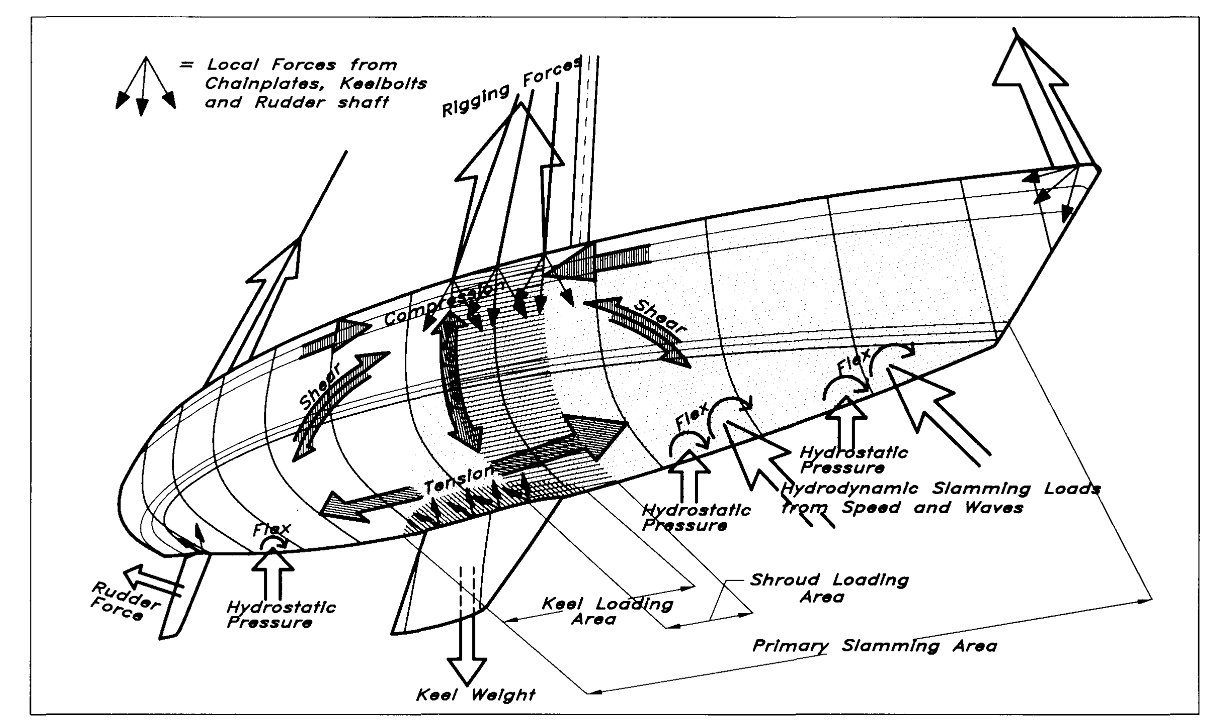
Another day of research…

Target Structure Analysis

- **Hull Shell Design**
  - **35% of LWL aft of Fwd Perpendicular**
  - **0 to 1’ off CL**
- **Determine loss of stiffness vs. stress cycle history (microcracking)**
- **Requires knowing load effects and test method bias**

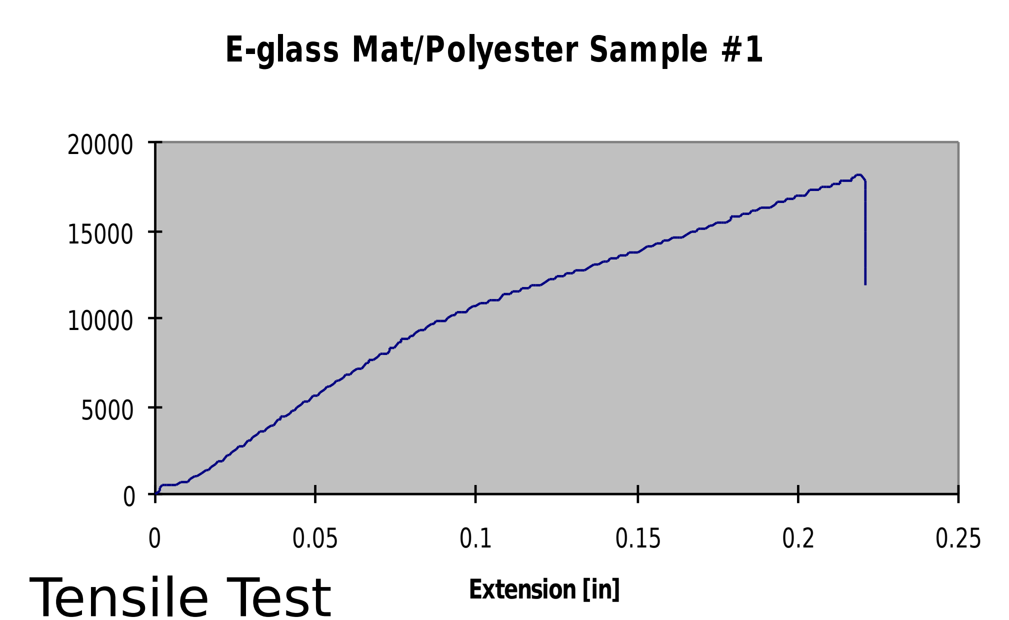
Loads on Target Area

- Hydrostatic
- Hydrodynamic
  - Slamming
  - Wave slap
  - Motion
  - Foil lift/drag
- Moisture



Quantified Material Properties

- Mostly linear stress/strain
- Brittle (0.8-2.7% ultimate strain)
- Stiffness and Strength Properties Needed (ASTM tests – W
  - Tensile
  - Compressive
  - Shear
  - Flex
  - Fatigue



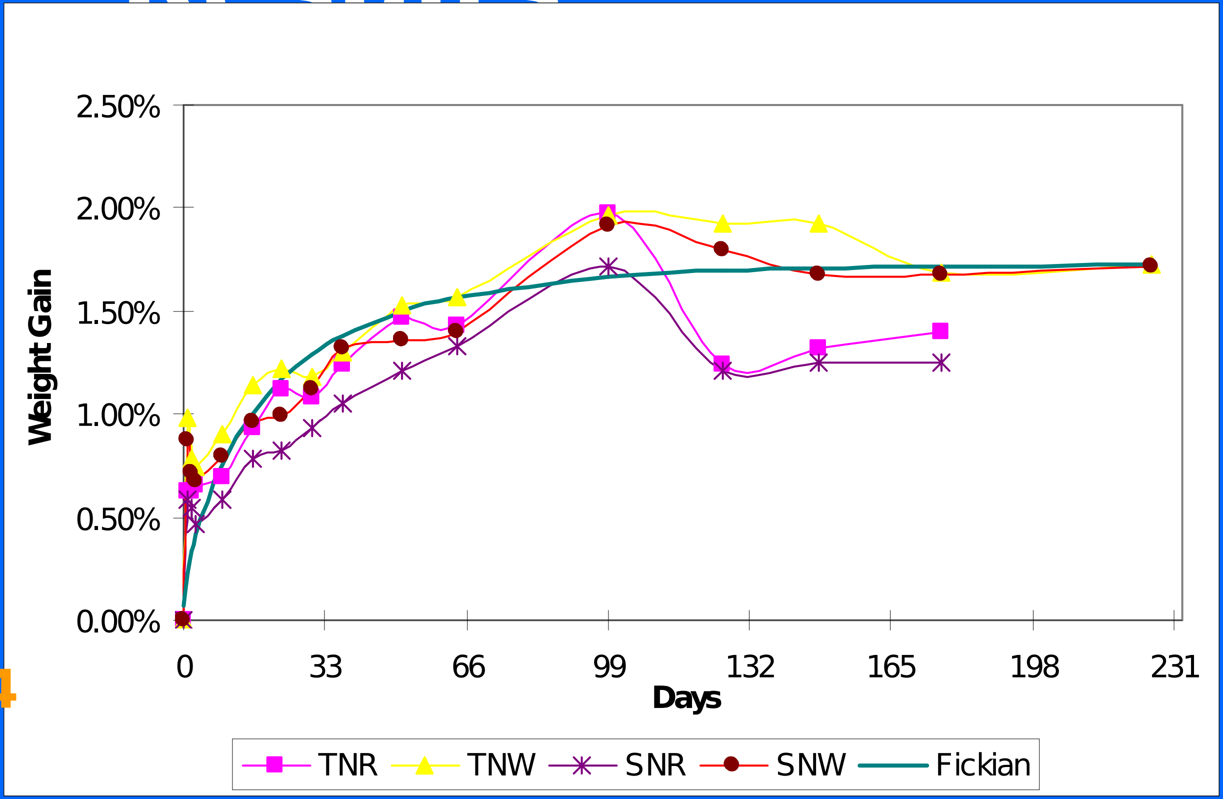
Tensile Test

Moisture Background and Tests

- **Porous materials (up to 2% weight)**
- **Few documented moisture failures**
- **Test results ambiguous (Stanford vs. UCSD)**
- **Test methods suspect (long-term vs. boiling)**
- **Fickian Diffusion**
- **Tested for 1 year**
  - **Dry, 100% relative humidity, submerged**

Moisture Absorption Results

- 1.8% weight gain for submerged
- 1.3% for 100% relative humidity
- Equilibrium in 4 months



These results were used for coupon and vessel test prepara

Finite Element Analysis

- Coupon, panel, global
- Element selection
  - Linear/nonlinear
  - Static/dynamic/quasi-static
  - CLT shell
  - Various shear deformation theories used (Mindlin and DiScuiva)
- COSMOS/M software
- Material property inputs from coupon tests

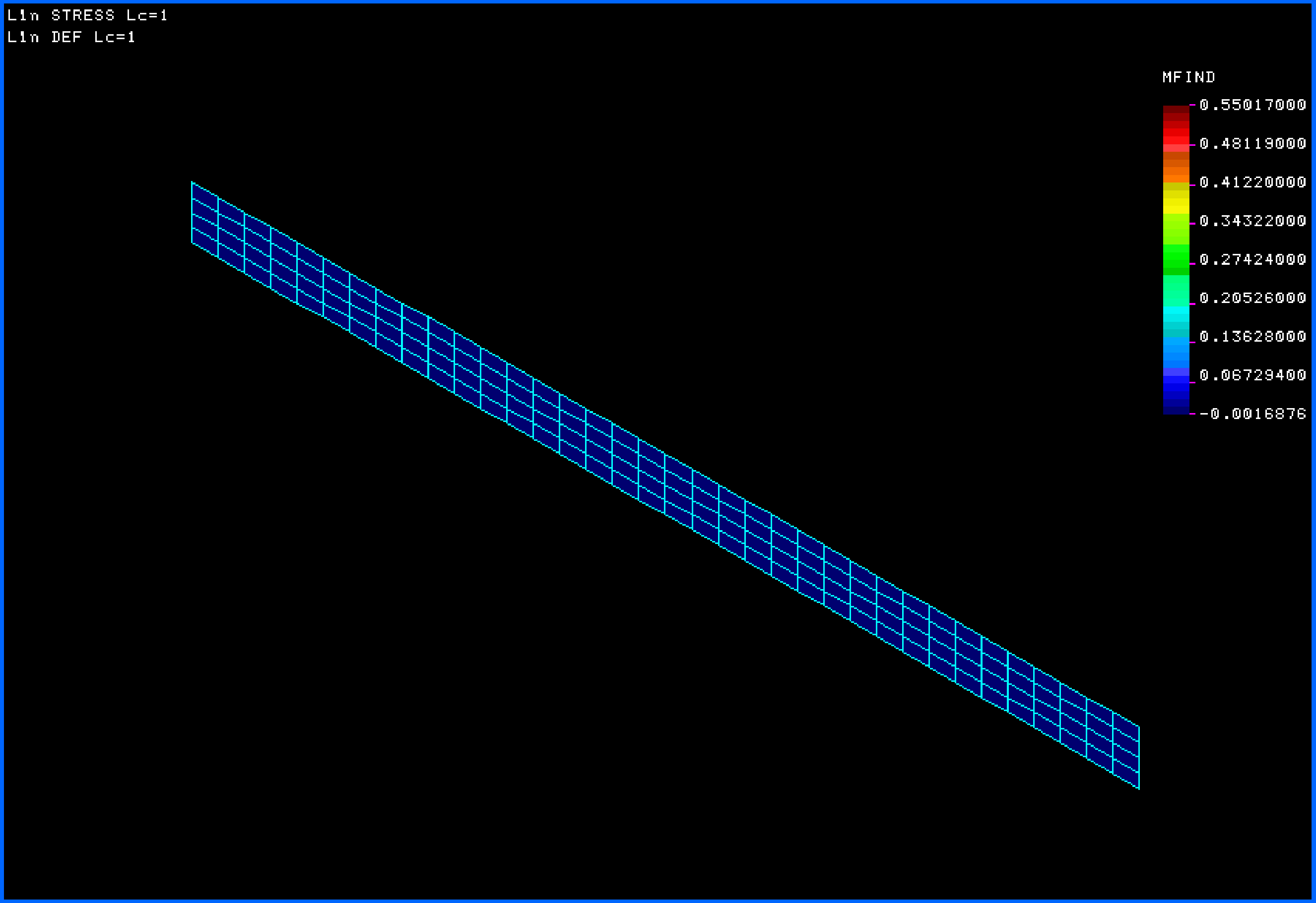
Coupon Test Results

- **Tensile Mod: 1.2 msi dry, -12% wet, -13% boiled**
- **Shear Mod: 0.56 msi dry, -11% wet, -16% boiled**
- **Comp Mod: 0.92 msi dry, -6% wet, -12% boiled**

- **Tensile Str: 11.3 ksi dry, -20% wet, -24% boiled**
- **Shear Str: 5.5 ksi dry, -11% wet, -22% boiled**
- **Comp Str: 25.3 ksi dry, -16% wet, -25% boiled**

Coupon FEA Results

Strains were within 2%, strength within 15%



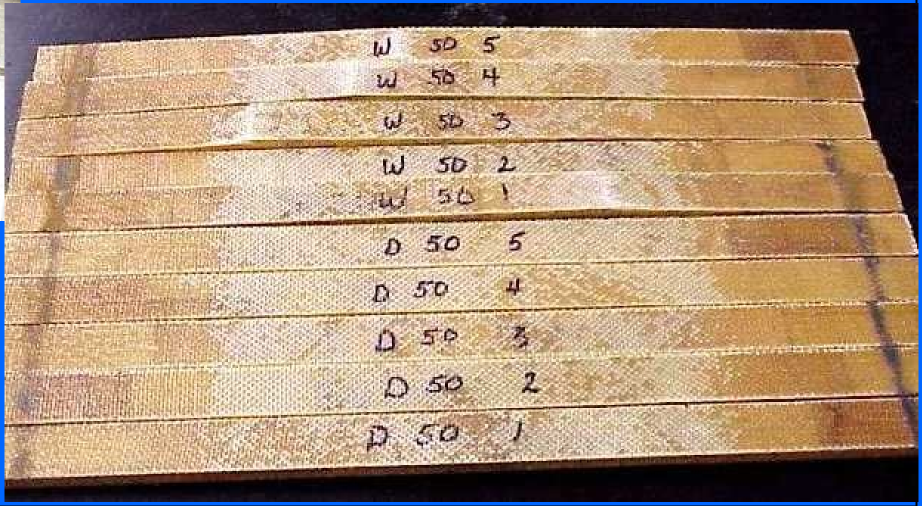
Fatigue Analysis for Vessels

$$E[D] = T \cdot f \int_0^\infty \frac{p(s_i)\,ds}{N(s_i)}$$

E[D] = the expected accumulated damage ratio
T = the time at frequency f
$p(s_i)$ = the probabilistic distribution of the number of stress cycles at stress s_i
$N(s_i)$ = the number of cycles to failure at stress s_i

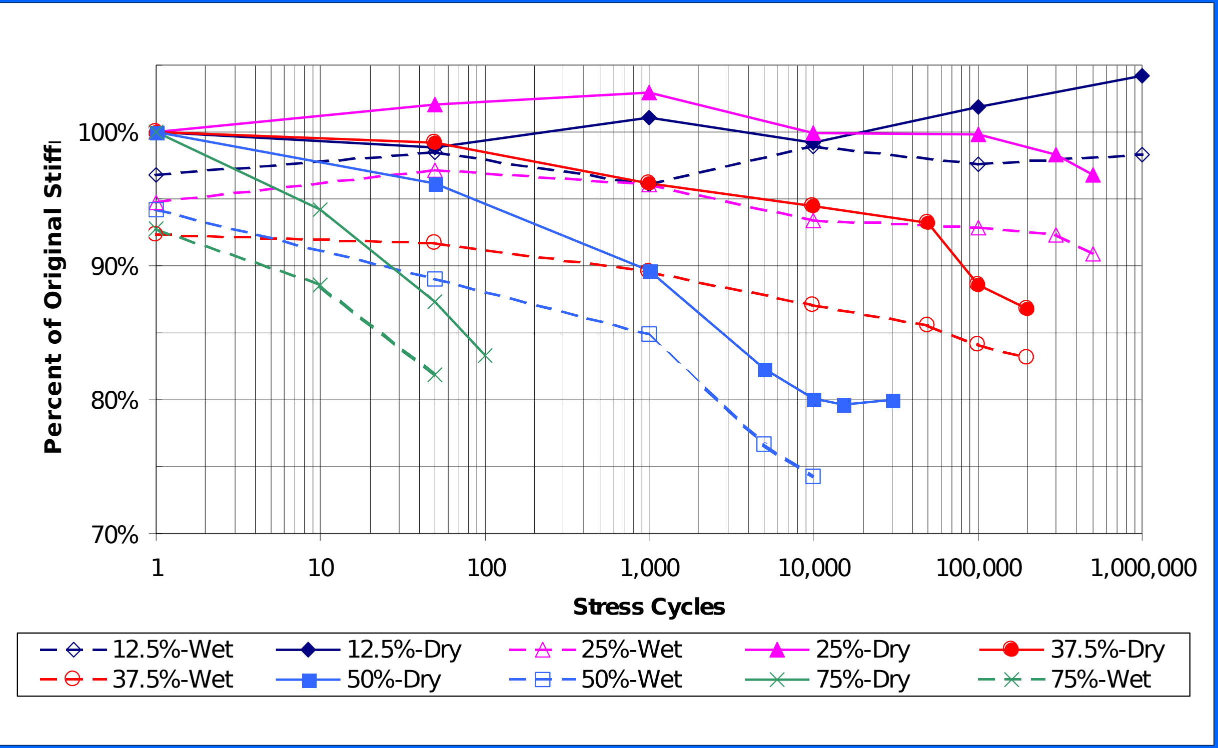
$$T \cdot f = p(\varphi) \cdot p(m) \cdot p(U_{ws}) \cdot \left[f(U_{ws}) + \frac{U(\varphi, U_{ws}) \cdot \cos(\varphi)}{U_w(U_{ws}) \cdot T_s(U_{ws})} \right]$$

Fatigue Testing



Fatigue Results – S/N Data

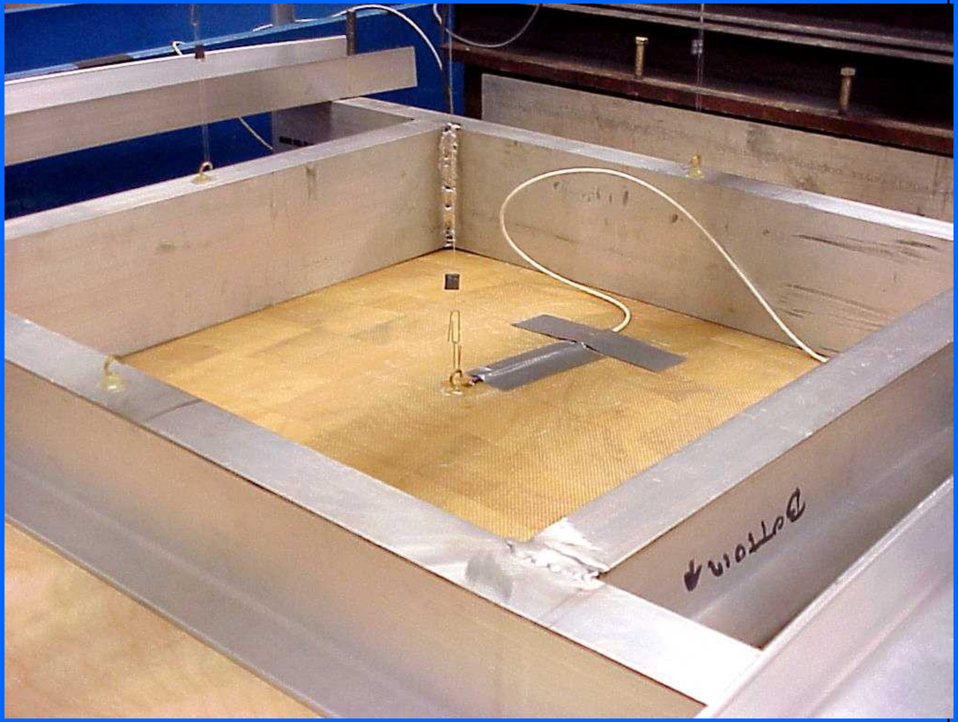
Moisture decreased initial and final stiffness but the rate of loss was the same.



Specimens failed when stiffness dropped 15-25%
No stiffness loss for 12.5% of static failure load specimen
25% load specimens showed gradual stiffness loss

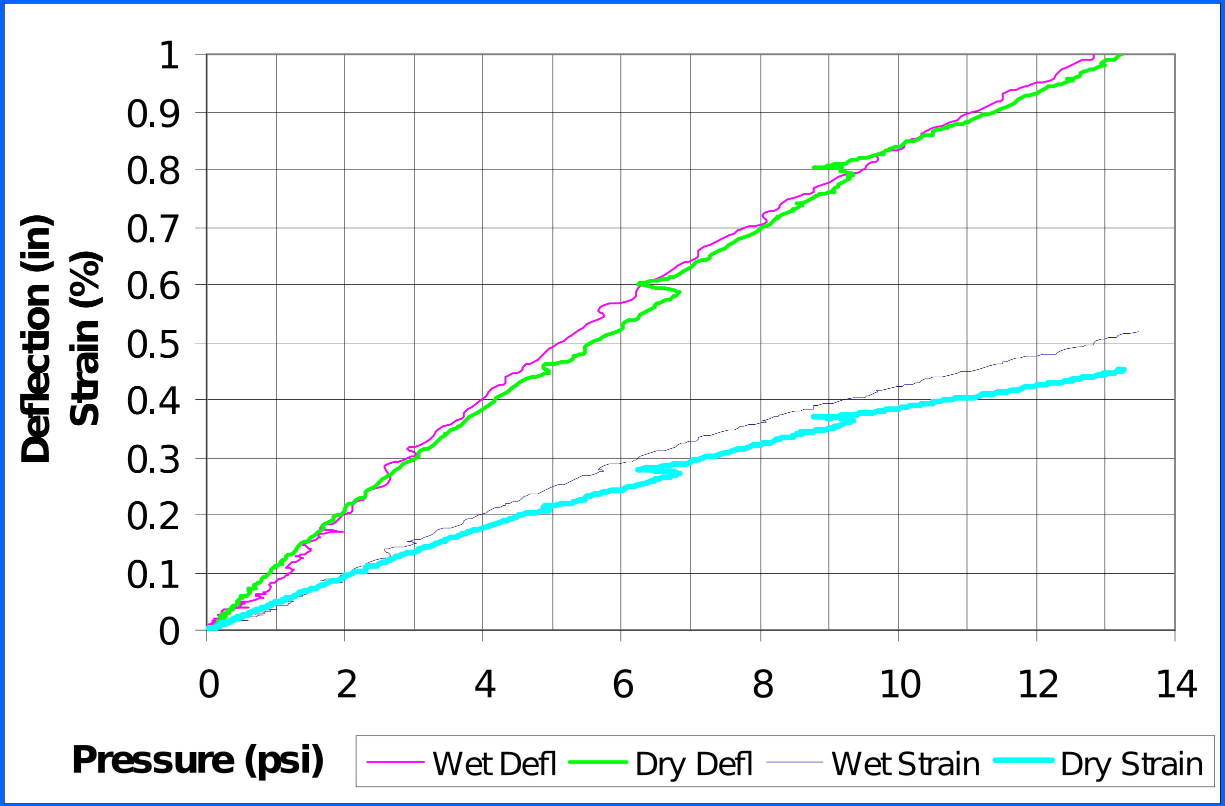
Panel Analysis

- Responds to USCG/SNAME studies
- Solves edge-effect problems
- Hydromat test system
- More expensive
- Correlated with FEA

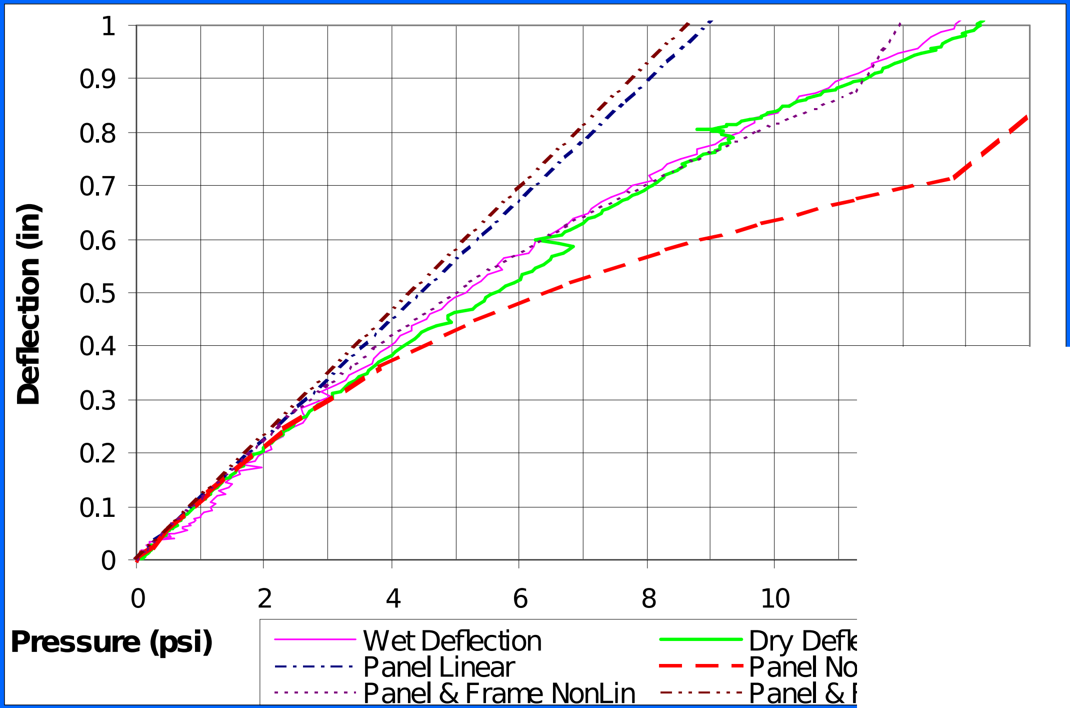


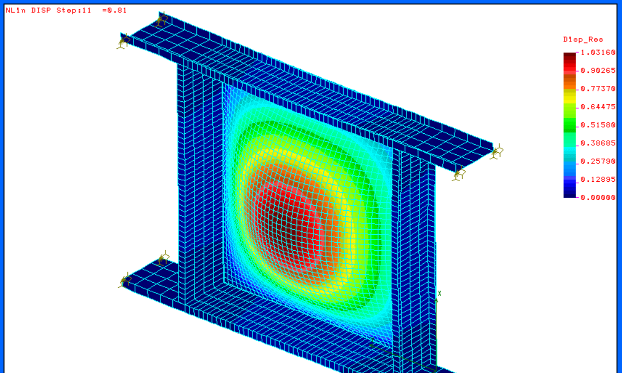
Panel Test Results

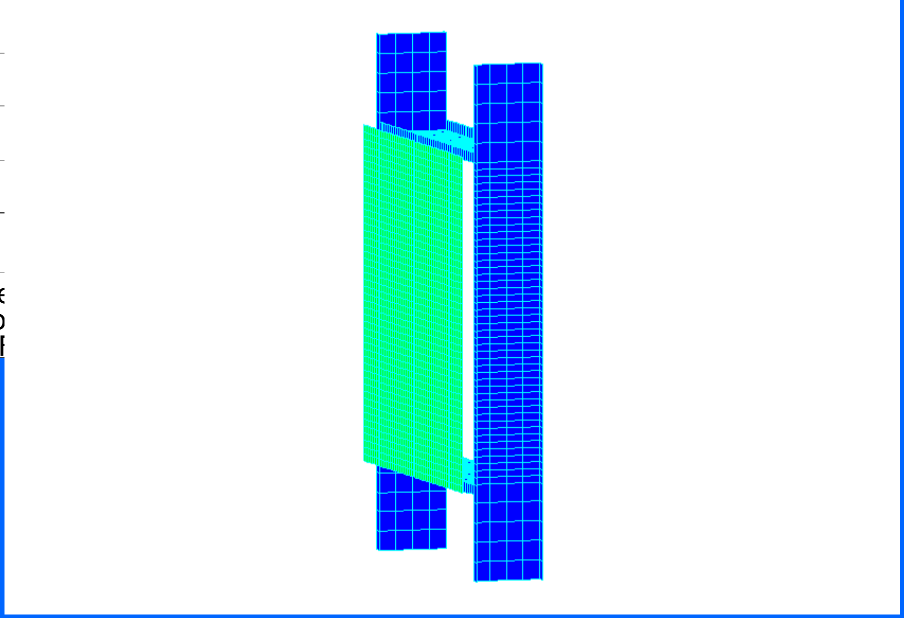
Wet vs. Dry results were similar to those from coupons; the one-sided wet specimens were marginally less stiff.



Panel FEA Results

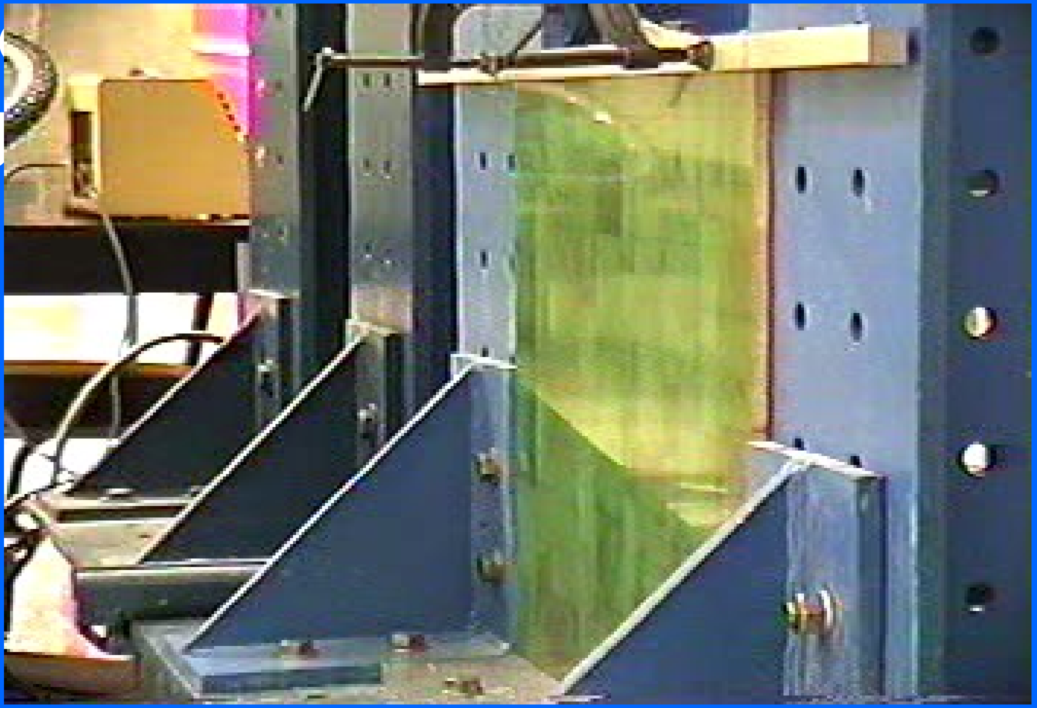






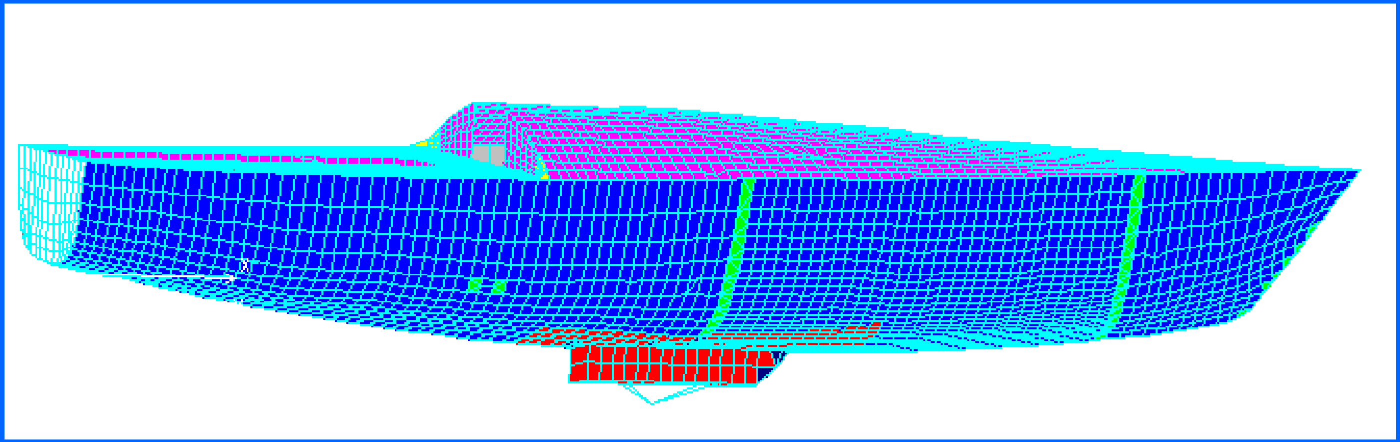
Impact Testing

- **The newest boat had the lowest stiffness.**
- **Did the collisi microcracking**



Yes, there was significant microcrackin g!

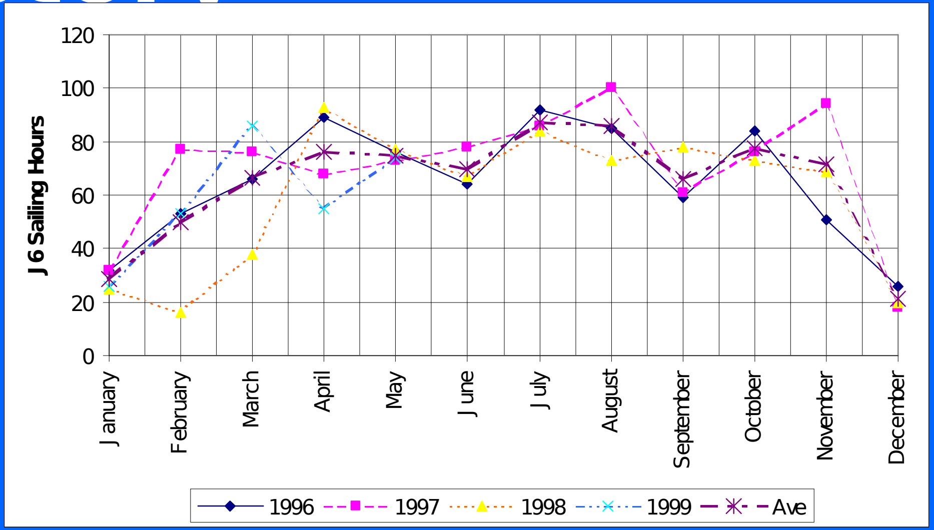
Global FEA



- Created from plans and boat checks
- Accurately models vessel
  - 8424 quad shell elements
  - 7940 nodes
  - 46728 DOF
- Load balance with accelerations

Full-Size Testing – Boat History

- **High Mileage – J6**
  - **Daily records for 3 years**
  - **Annual records since new**
  - **NOAA wind records for the same period (daylight)**
  - **Course distribution**
  - **Velocity prediction program for speed**



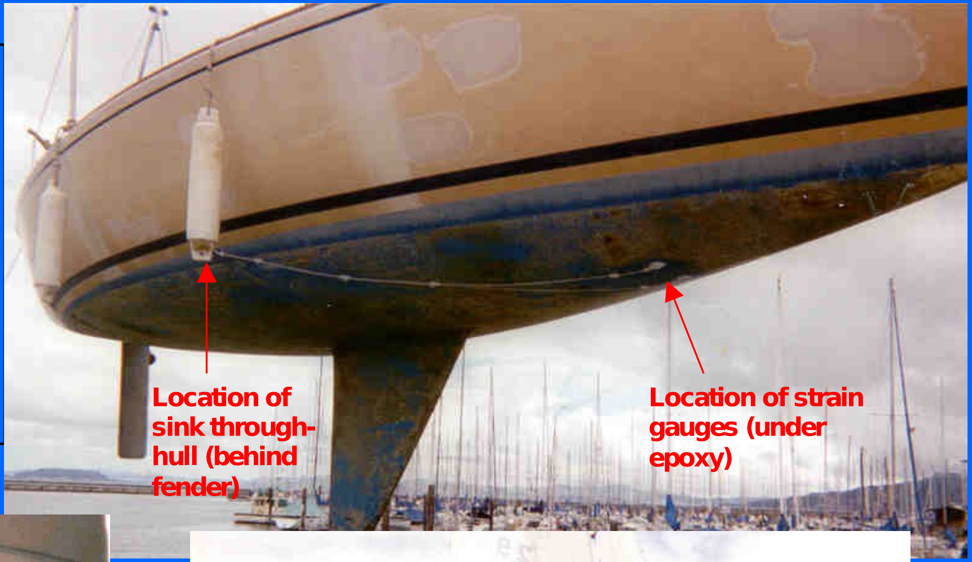
The Bottom Line for J6:

- **11,300 hours sailing**
- **10,200,000 wave encounters**
- **The “low mileage” boat had 740 hours and 600,000 waves**

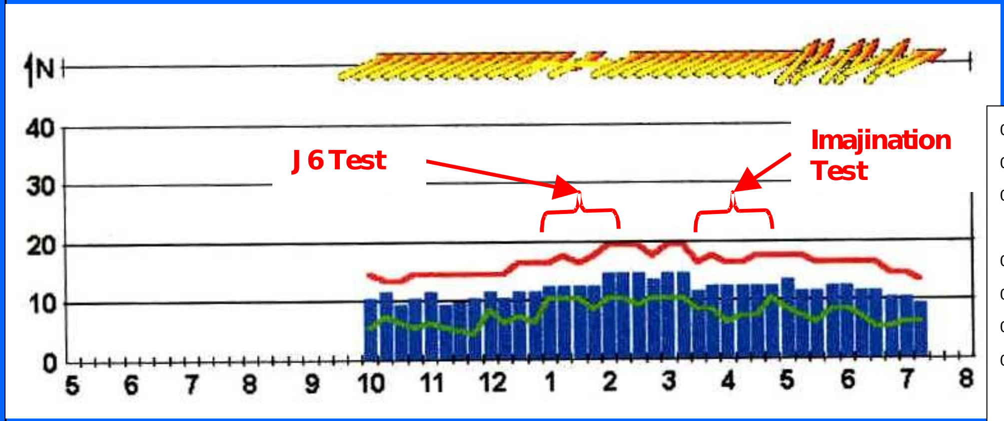
On-The-Water Testing- Set Up

Instrument Locations for Boat Tests

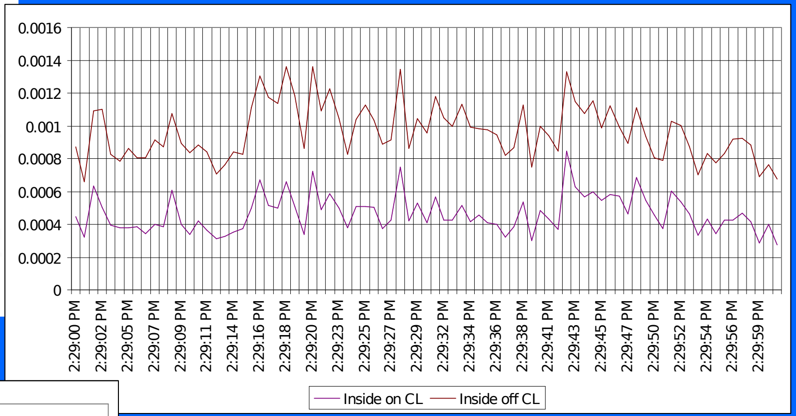
Instrument	*Location*
Strain Gage #1	Portside shroud chainplate
Strain Gage #2	Forestay chainplate
Strain Gage #3	Inside hull on centerline
Strain Gage #4	Inside hull off centerline
Strain Gage #5	Outside hull on centerline
Strain Gage #6	Outside hull off centerline
Accelerometer	Bulkhead aft of strain gages



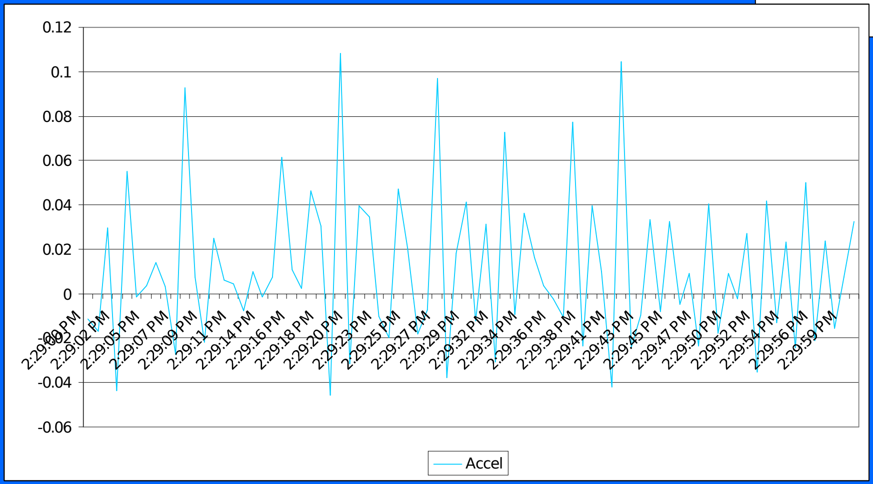
Data Records



Wind

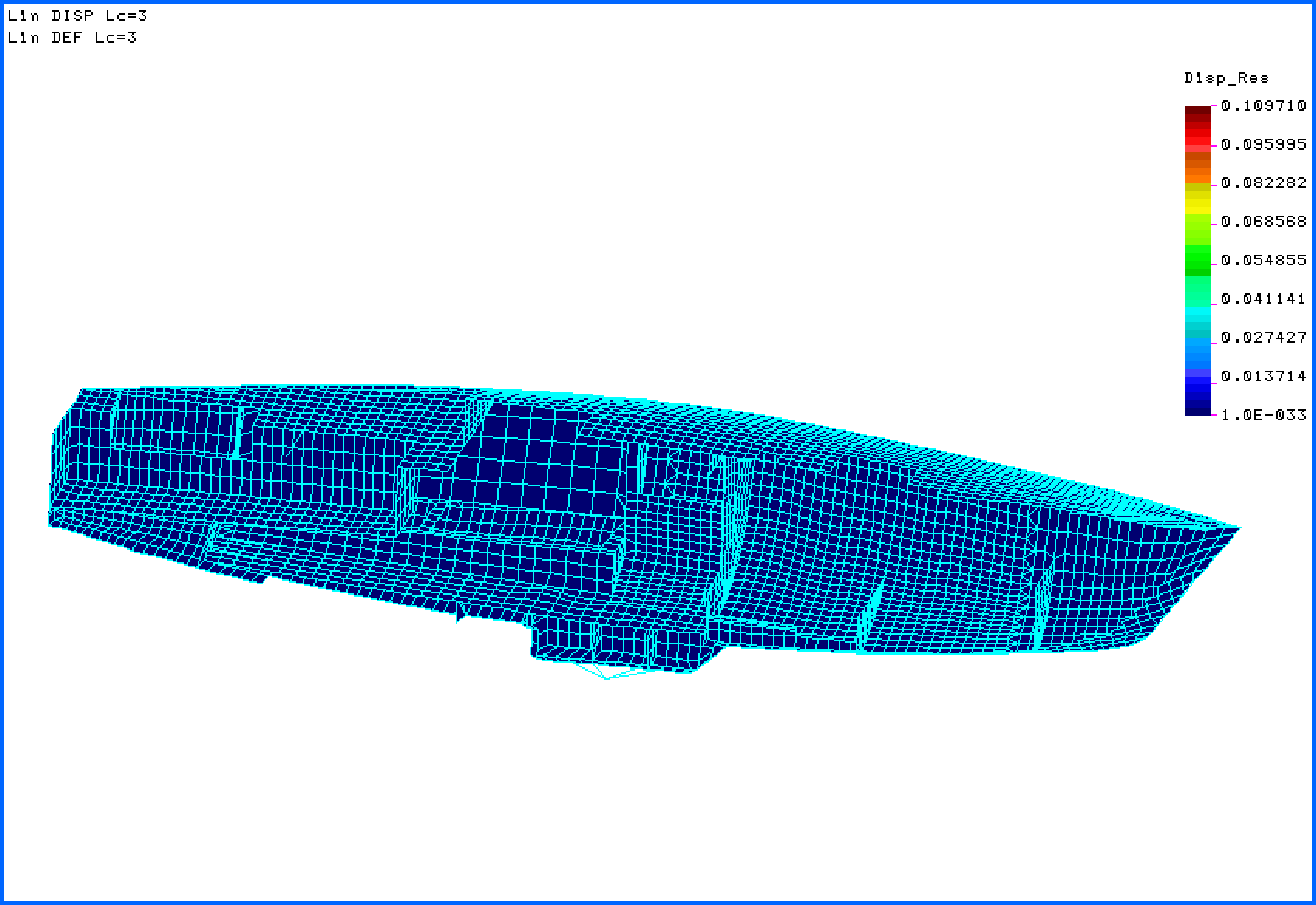


Strains

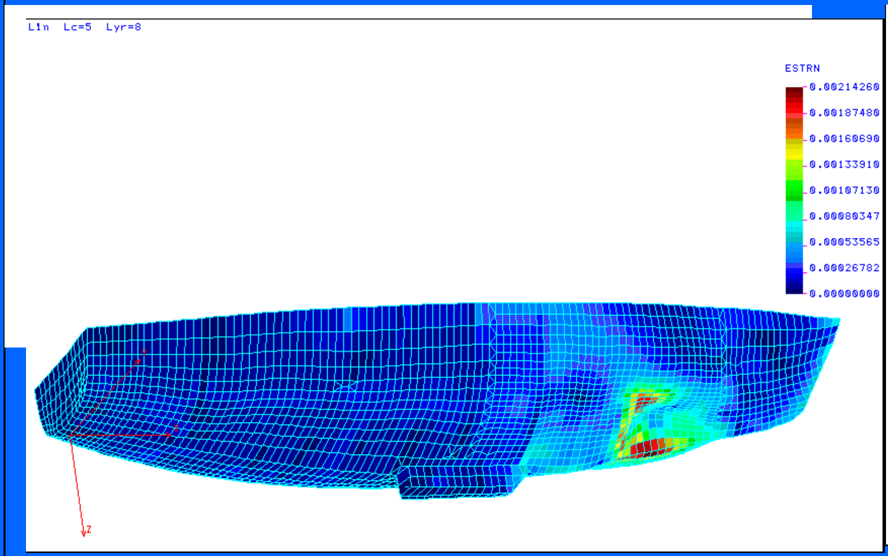


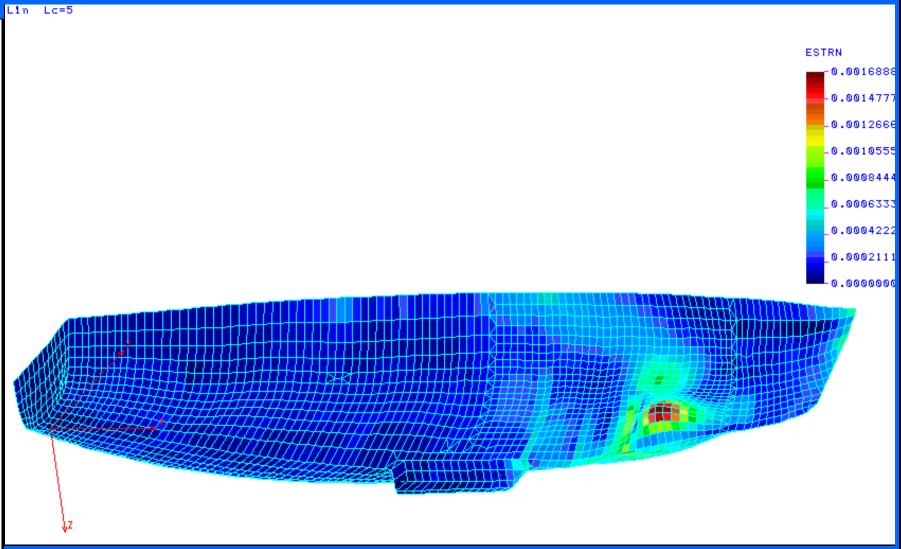
Accelerations

Dockside String-Test FEA



Slamming FEA

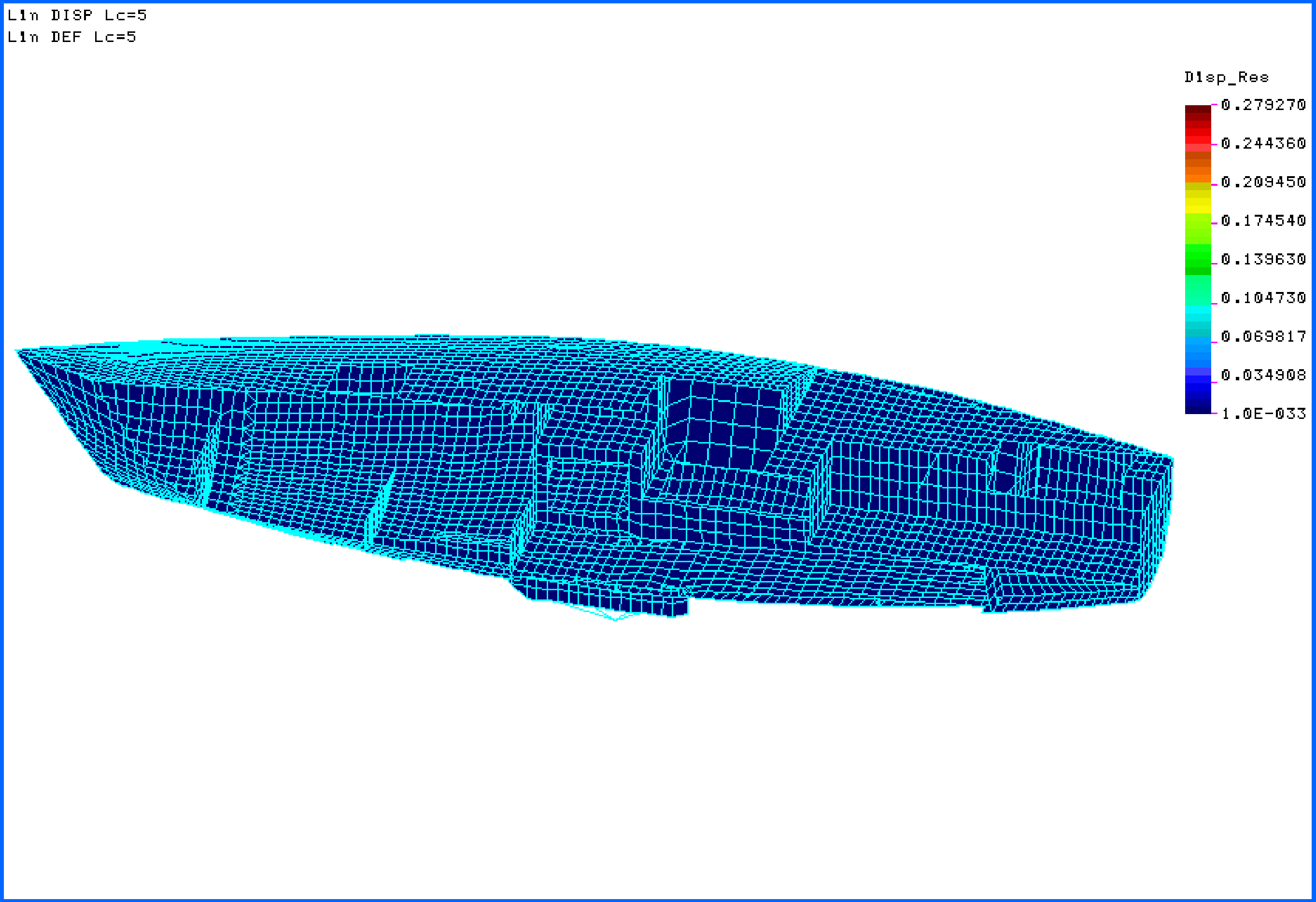




Inner Skin WS=22.5 knots Outer Skin

Using measured accelerations and wave heights from pictures strains were 0.21% for inner and 0.17% for outer. (23% & 18% of ultimate strain)

Slamming FEA



Comparison of Results

- **Slamming (Low Mileage Boat- “Imajination”)**
  - **Peak measured 0.136%**
  - **Ave. of measured peaks 0.117%**
  - **FEA prediction 0.125%**

With all the fatigue cycles included, the stiffness

	Imajination	J 6
Predicted Stiff Reduction	-3%	-14%
Measured with Strain Gauges	-4%	-18%
Global "String Test"	-14%	-52%

The Most Useful Conclusions

- The Metal Ship Fatigue Design Process can be extended to composite vessels
- Current factors will lead to fatigue lives of 10-30 years
- Visual clues for fatigue failure are evident
- Stiffness loss may be a better method of prediction
- Good FEA accuracy requires a lot of work!

Thanks!

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- Gerald Bellows
- Paul Jackson
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Go Bears!